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7. Design Studies to Maximize the Discharge Burnup of Liquid-Metal-Cooled ATW Systems,

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The main purpose of the accelerator transmutation of waste (ATW) system is to reduce the radiotoxicity of the high-level waste to be disposed of in the repository by removing the transuranic (TRU) elements from the spent fuel and transmuting them in the ATW blanket. The radiotoxicity reduction is primarily achieved by reducing the fraction of the initial TRU inventory that is not transmuted and lost to the waste stream. To minimize this fractional loss, it is necessary to maximize the discharge burnup and to minimize the reprocessing and fuel fabrication losses.[1] The maximization of the discharge burnup is also required to reduce the fuel cycle cost of the ATW system.[2] In this paper, we present the preliminary results of physics design studies aimed at maximizing the discharge burnup of lead-bismuth eutectic (LBE) and sodium-cooled ATW blankets fueled with TRU-Zr/Zr metallic dispersion fuel. The focus is on discharge burnup maximization in the physics design of the blanket; the feasibility of attaining this high, targeted burnup with the selected fuel form remains to be demonstrated.

The discharge burnup is proportional to the average power density and the fuel residence time and is inversely proportional to the fuel volume fraction and the TRU fraction in fuel. This relation suggests that the discharge burnup can be maximized by designing for the maximum power density and fuel residence time and the minimum fuel volume fraction. However, these quantities are interrelated and limited by various design constraints:

1. The TRU fraction in fuel is determined such that the desired subcriticality level is achieved for the selected blanket configuration and fuel management scheme. This quantity is constrained by the maximum volumetric fraction of fuel particles (assumed here to be TRU-10wt%Zr) in the dispersion fuel, which is assumed to be 0.25.
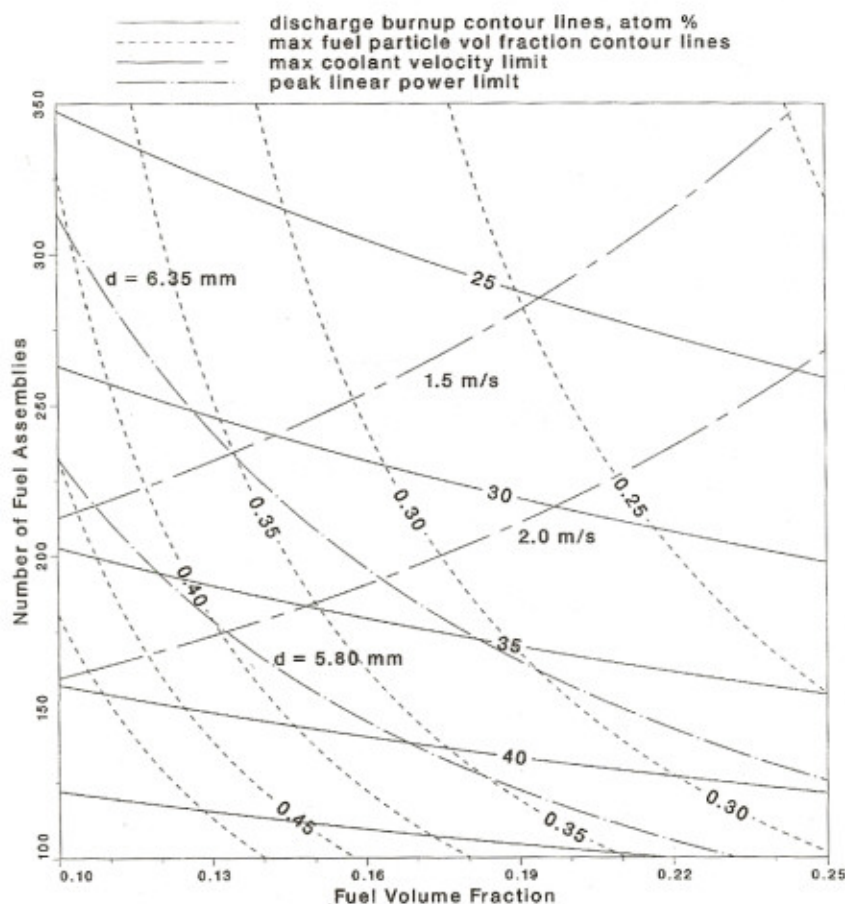

Fig. 1. Discharge burnup and fuel particle volume fraction of the LBE-cooled ATW blanket (fuel volume fractions at operating condition).

TABLE I

Correlation Coefficients and Maximum Correlation Errors

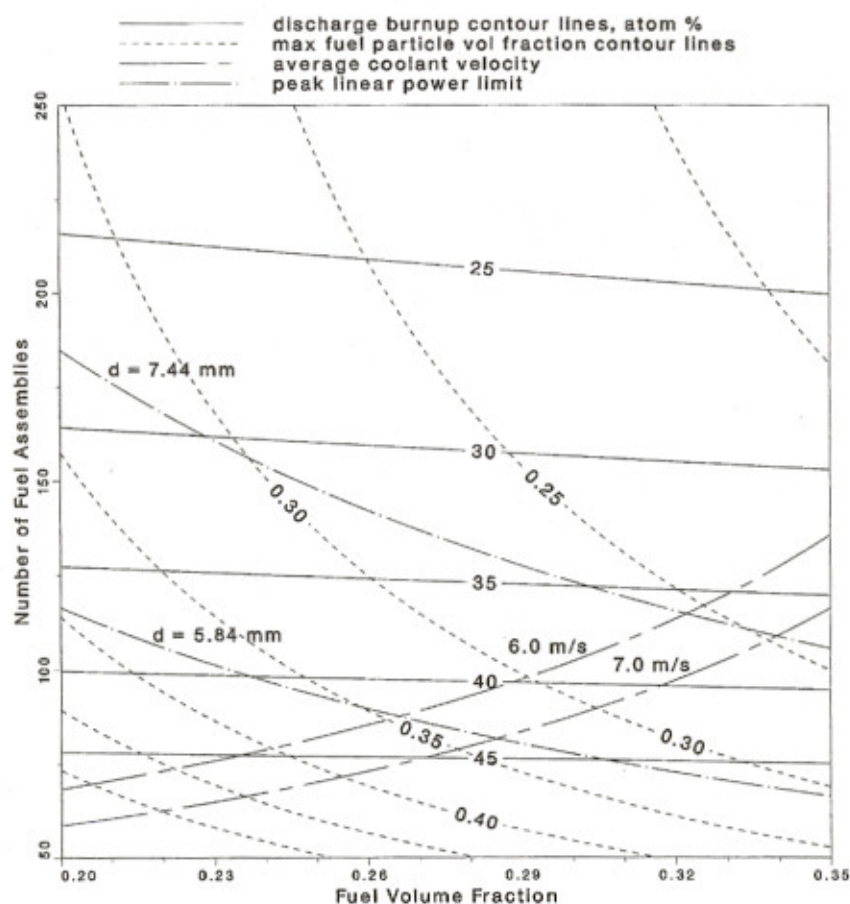| Parameter	Correlation Coefficients				Maximum Error (%)
	1	2	3	4	
LBE System					
Fuel Particle Vol. Fraction	4.1990	−1.6722	1.8174×10^{-2}	6.3017×10^{-2}	0.24
Discharge Burnup (%)	2.0143×10^{-4}	5.8707×10^{-5}	-5.5407×10^{-3}	1.3151×10^{-2}	0.55
Sodium System					
Fuel Particle Vol. Fraction	4.2475	−1.2972	3.3750×10^{-2}	2.8152×10^{-2}	0.79
Discharge Burnup (%)	9.0008×10^{-5}	1.0791×10^{-4}	-4.1473×10^{-3}	1.3580×10^{-2}	0.73

Fig. 2. Discharge burnup and fuel particle volume fraction of the sodium-cooled ATW blanket (fuel volume fractions at operating condition).

2. The peak fast fluence and the discharge burnup are limited by the need to ensure the fuel pin integrity. In the proposed dispersion fuel, fission products are retained within the fuel particles, which are contained within the matrix. As a result, a higher burnup can be achieved compared to the conventional metallic fuel, and thus, the discharge burnup is not likely to constrain the design. On the other hand, there is likely a fast fluence limit for the core structural material (assumed to be HT-9), and the peak fast fluence limit is assumed to be $\sim 4.0 \times 10^{23}$ n/cm². This peak fluence limit on the blanket structural material constrains the fuel residence time.

3. The peak linear power is constrained by the need to limit the peak fuel centerline temperature. The minimum fuel volume fraction required to satisfy the specified constraint on the peak linear power increases as the power density increases.

4. The power density and coolant volume fraction are interrelated for adequate cooling. For a specified coolant velocity, the minimum coolant volume fraction increases as the power density increases. In the case of lead-based coolant, the coolant velocity is further limited because the corrosion and erosive wear of core structural materials are intensified as the coolant velocity increases.

Subject to these design constraints, parametric studies were performed to determine design characteristics yielding the maximum discharge burnup for an 840-MW(thermal) ATW blanket. By adopting a short irradiation cycle approach to limiting the burnup reactivity loss,[3] the present study focused on optimizing the blanket configuration and material volume fractions to maximize the discharge burnup under key design constraints. A fuel residence time of 4 yr at a 75% capacity factor was assumed with a cycle length of $\frac{1}{2}$ yr. Blanket performance was evaluated for the equilibrium fuel cycle attained by repeated recycle of the TRU discharged from the blanket with light water reactor–discharge TRU used as makeup for the TRU consumed by fission each cycle. The blanket power distribution was flattened by optimizing the split of the TRU loading among the concentric planar zones of the blanket. The number of different blanket zones differing in the TRU fraction of the fuel was two and three for the sodium- and the LBE-cooled systems, respectively.

For each blanket configuration and material volume fraction, the TRU-10Zr particle fraction in fuel was determined such that the k_{eff} at the beginning of cycle is 0.97. It was found that the average fuel particle volume fraction e_{tru} can be accurately correlated with the number of fuel assemblies N_f and the fuel volume fraction v_f as

$$e_{tru} = a_1/N_f v_f + a_2/N_f + a_3/v_f + a_4 , \qquad (1)$$

where a_1 to a_4 are correlation coefficients. As a result, the average discharge burnup can also be correlated as

$$B_d = 1/(b_1 N_f v_f + b_2 N_f + b_3 v_f + b_4) , \qquad (2)$$

where b_1 to b_4 are correlation coefficients. The correlation coefficients and maximum correlation errors are shown in Table I. These relations show that the required TRU fraction and discharge burnup increase monotonically as the fuel volume fraction and blanket size decrease. For a given blanket size and fuel volume fraction, the sodium system requires a higher TRU fraction than the LBE system because of greater neutron leakage and absorption, and thus, it results in a lower discharge burnup. The parametric studies also showed that the discharge burnup is pro-

portional to the peak fast fluence, and the maximum discharge burnup achievable under the peak fast fluence limit was found to be ~30% for the LBE system and ~33% for the sodium system. The neutron energy spectrum of the sodium is not as hard as that of the LBE system, and thus, the fast-fluence-to-burnup ratio is slightly lower.

Figures 1 and 2 show the contour plots of the discharge burnup and the maximum TRU fraction along with the curves representing the minimum blanket size required to satisfy the coolant velocity and peak linear power constraints. The peak linear power limit curves for two different pin diameters are provided in the figures. In determining the feasible domains for the constraints on the coolant velocity and the peak linear power, analytic formulas based on simple heat transfer calculations were employed. One can see that the maximum fuel particle volume-fraction limit of 0.25 is more demanding than the peak linear power constraints. In the LBE system, if the maximum coolant velocity limit is 2.0 m/s, the optimum fuel volume fraction to maximize the discharge burnup while satisfying the design constraints (on-peak linear power, coolant velocity, and fuel particle volume fraction) is ~0.21. In this case, an average discharge burnup of ~28% is achieved with a blanket size of ~230 assemblies. The sodium system can exploit a higher coolant velocity (and much lower coolant volume fraction), producing a more compact, higher power density core. Figure 2 shows that if the average coolant velocity is 6.0 m/s (typical value), the optimum fuel volume fraction is ~0.32. This yields an average discharge burnup (unconstrained by the peak fast fluence limit) of ~36% with ~120 fuel assemblies. To satisfy the peak fast fluence limit, the fuel residence time can be reduced slightly, or the blanket size can be increased slightly.

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